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6. AUTHOR(S)

Prof Allexander Konovalenko

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Institute of Radio Astronomy (RIAN)
4, Krasnozanmennaya Str
Kharkov 310002
Ukraine

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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Institute of Radio Astronomy (RIAN) as follows: The contractor will investigate the usable frequencies and effective radiated powers required to penetrate the ionosphere, reach the sun and return at detectable levels; the best duty cycles and waveforms needed to coordinate Sura radar opeations with the UTR-2 antenna and the ionospheric effect on transmitted radar waves. Radar tests planned for the Sura and UTR-2 facilities will be correlated with various solar monitoring observatories providing images of the solar coronan and the solar disk. All work is to be performed as described in the proposal.

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To: Liason Officer, Kent Miller
European Office of Aerospace Research and Development
PSC 802 Box 14
FPO AE 09499-0200

From: Prof. Alexander A. Konovalenko
Department of Decametric Radio Astronomy
Institute of Radio Astronomy
4, Krasnoznamennaya Str.
310002 Kharkov
Ukraine

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FINAL RESEARCH REPORT ON THE 1997-98 EOARD PROJECT SPC-~~98-4052~~: 97-4079

THE USE OF HIGH FREQUENCY SOLAR RADAR TO DETECT CORONAL MASS EJECTIONS

1. Introduction

In our preliminary report, we described the purposes of the project, the experimental facilities, the characteristics of the specially developed equipment, and preliminary results of the experiments. In the final report we summarize the information in the preliminary report and present new information on the experiments conducted and the results obtained by the Institute of Radio Astronomy, Kharkov, Ukraine, after September 1997. This research project was initiated by Dr. Paul Rodriguez, Naval Research Laboratory, USA. The main task of this project is the preparation and realization of radar investigations of the sun with the goal of detecting coronal mass ejections (CMEs). A CME is one of the most important and interesting phenomena in the study of solar physics and solar terrestrial relations. According to preliminary estimations high frequency radars can be one of the most effective means for the detection of these phenomena. This technique is most effective if used in a bistatic configuration, for example, the use of the Russian Sura high frequency transmitter and the Ukrainian UTR-2 receiving antenna array.

2. Instrumentation

The UTR-2 radio telescope is the world's largest decametric array that operates in the frequency range 8 to 32 MHz . The full effective area of UTR-2 is near 150,000 square meters for the zenith orientation and the beam width ranges from 20 minutes to 1.5 degrees of arc. The radiotelescope has a T-shaped configuration, The dimensions of the

N-S arm [Figure 1] is approximately 1800 m by 60 m; the dimensions of the E-W arm [Figure 2] is approximately 900 m by 60 m. The total number of receiving broadband dipoles is 2040. The system noise temperature is determined by the brightness temperature of the galactic background, corresponding to a range of several 10s of thousands of Kelvins to several 100s of thousands of Kelvins at such low frequencies. The distributed antenna amplifier system consists of broadband, high linearity amplifiers. This system provides compensation for amplitude losses in the long cables from the dipoles to the control center, thus providing maximum sensitivity in the radiotelescope. The time-delay phase system used in the radiotelescope provides the same beam position for all frequencies used. There is the possibility of electronic steering of the beam in a broad cone at all azimuths, as well as simultaneous observations with 5 spatially separated beams. The radiotelescope allows us to use it in a wide variety of parallel output configurations, including independent steering of the E-W and N-S antennas. This instrument satisfies all requirements for the solar radar experiment and allows us to receive weak signals in the presence of strong man-made and natural ionospheric interferences. Special hardware and software has been designed for conducting the experiments of this project.

2.1 Equipment for monitoring interference

A dedicated spectrum analyzer was used to visually monitor the presence of interference during the experiment. This facility includes a broadband Hewlett-Packard spectrum analyzer, multichannel receiving system with a resolution of 0.3-10 kHz per channel, and a broadband correlation analyzer. This approach was used to select the transmission frequency of the Sura transmitter.

2.2 High speed digital registration

A six-channel tape recorder was used to record the signals from the UTR-2 North-South and East-West arrays for solar and moon reflection experiments. The bandwidth of each channel is 40 kHz. We used rubidium standards for synchronization of all receivers. We used a high speed A/D converter to acquire the data for input to a computer. The output volume of data is approximately 2 or 3 Gigabytes for each experimental session. This system allowed us to synthesize a pencil beam for the UTR-2 array. For the Moon experiments this facility allowed us to obtain very accurate measurements of the frequency of the reflected wave, corresponding to frequency resolution of $\Delta f = 0.02$ to 0.05 Hz. A pilot signal is used with the tape recorder to compensate for tape speed wobble. This accuracy allows us to obtain an estimate for scattering parameters at 9 MHz in the scattering medium.

2.3 Multichannel digital correlometer

The intermediate frequency signals with bandwidths up to 40 kHz from four radio receivers were input to four digital correlometer with 2 x 64 and 2 x 48 lags. This allowed us to obtain a frequency resolution of nearly 1 kHz. The autocorrelation function

was determined in real time with an integration constant of about 1 second. These data were input to a small computer for storage and Fourier analysis. The maximum frequency coverage is about 100 kHz, corresponding to a maximum Doppler shift near 9 MHz, or a plasma flow velocity of 1500 km/sec. One-bit digitization is used in the digital correlometer. This leads to a decreased sensitivity by a factor of 1.57, but allows us to reach high reliability and stability of the equipment. Furthermore, this equipment allows us to reach a higher speed of sampling, with minimum memory requirement. The nonlinear element at the input of the system increases the problem of intermodulation interference. During this project, the nonlinear problem was studied theoretically and experimentally. It was shown that when the full power of the interference signal did not exceed the full power of the noise in the working frequency band, the interference is not significant. A similar situation exists during our experiments.

2.4 Video recorder

The video recorder was used to record the analog output of two radio receivers with bandwidths of 40 kHz. The next step of data analysis is similar to the processing done in the VLBI URAN data analysis. The VLBI URAN system is the Ukrainian Decametric Very Long Baseline Interferometer. This facility includes mixers to transform intermediate band frequencies to baseband. The output of each receiver is split into In-phase and Quadrature channels. The number of quantization levels is four. The signals are sent by computer in digital form to a video recorder. Furthermore, precise time signals are recorded on the video recorders. Data processing begins in the off-line regime with tape playback to a high-power computer, followed by spectrum analysis and determination of all parameters of radio emission.

2.5 Multichannel Postdetection Recording

Thirty radio receivers were used in the frequency range from 8 to 32 MHz in the 5-beam mode of the UTR-2 array. The signal from the output of the detectors and integrators were digitized. The minimum sampling period is near 2 milliseconds. This facility was used to obtain reference signals by reflection from the moon and monitoring standard radio sources; this provided a method of monitoring the effects of ionospheric influence on the received signals. For the Moon reflection experiments the frequency band is from 0.3 kHz to 4 kHz, with time constant near 5 ms. The level of reflected signals are not known apriori because the amplifications of each channel are different. Furthermore, in order to reduce ionospheric refraction effects, the received signals are distributed along spatially separated beams. For the observation of reference radio sources, the frequency band is 4 kHz to 40 kHz, with time constants of 1 sec to 60 sec.

2.6 Sporadic solar radio emission facility

This is a multichannel receiving system with high dynamic range and operational range from 9 to 30 MHz. The time resolution is near 100 milliseconds. As a rule, the observations were carried out in eight channels with frequency bands approximately 10

kHz near the frequencies of 8.9, 10, 12.6, 14.7, 16.7, 20, 25, and 30 MHz. Furthermore, it is possible to use a broadband dynamic spectrograph and heliograph for spatial localization of emission sources. This system allows to record all kinds of sporadic radio emission and corresponding dynamic spectra.

3. Experimental Research and Observations

From July to September, 1997, we performed several sessions of radar experiments on the sun and moon. The parameters of the transmitted signal and protocol of the experiment was sent in the initial report submitted to EOARD by NIRFI (Radiophysical Research Institute, N. Novgorod). Because of ionospheric propagation and the high power of transmission the transmitted signal was received by UTR-2 through the sidelobes. These signals were used for time registration, an independent check of the modulation pattern, transmitted frequency, and power. During the solar experiments the length of transmission was 15 minutes, followed by 15 minutes of reception by UTR-2. The signal reception was done using the recording systems described in items 2.2, 2.3, and 2.4. After the end of the 15-minute reception interval, a background signal level was recorded for another 15-minute interval. A calibrating noise generator was used to calibrate and test all facilities also. The working regimes during the summer of 1997 are shown in Tables 1 through 6. The sun radar experiment was supported by the results of the moon radar experiment using the equipment described in items 2.2 and 2.5. The principal goal of the moon experiment is the calibration of the power, determination of ionospheric influences (absorption, refraction, and scattering), as well as the estimation of the possibility of moon surface mapping. By using a few beams in the moon experiment we observed at most times the refraction of the received signal. One example of data recorded for Moon observations by the equipment described in Section 2.5 is shown in Figure 3. The more intense pulses with constant amplitudes correspond to the 'direct' signal transmitted by the SURA radar; we receive this signal by ionospheric reflection with very little time delay. The less intense pulses between the 'direct' pulses correspond to the signal reflected from the Moon. As can be seen, the reflected pulses are detected with great reliability. The intensity fluctuations are determined by the effects of the propagation medium. According to the radar equation, there is agreement between calculated and measured signal amplitudes, when we take into account the parameters of transmitting and receiving antennas. With the equipment described in Section 2.2, we observed the dynamic Doppler shifts determined by Moon's orbital motion and Earth's rotation. The maximum time and frequency resolution in this experiment was 20 microseconds and 0.02 Hz. It is very important to know solar activity conditions during solar radar experiments, therefore we have continuous monitoring of solar sporadic radio emissions with the items described in 2.6. In the July and August experiments, sporadic solar emissions were practically absent. In September, the situation changed dramatically; there were several Type III solar storms. On the September 17 we detected a strong and unique high power emission from the sun in the frequency interval from 10 to 30 MHz with a sharp cutoff below 10 MHz, as shown in Figure 2 of the preliminary report. Because the moon cannot always be used as a calibration source during solar radar experiments we have investigated alternate methods for determining ionospheric

effects on the reflected signal. This procedure is especially important for low frequencies. One alternate method is to observe passively for sporadic solar radio emissions. Another method is to use cosmic compact radio sources to estimate the ionospheric effect, such as the radio source Virgo A, which is convenient to use in summer daytime. An experiment on 15 September, 1997, observing Virgo A in daytime confirmed the absence of ionospheric effects. A nighttime experiment with Cassiopeia A showed large variability in ionospheric conditions for a 5-day interval. Figure 4 shows the registration of reference radio sources Cassiopeia A on the central beam of the UTR-2 radiotelescope at frequencies of 25, 20, 16.7,. 12.7, 8.916, and 8.925 MHz [highest frequency is at the top of scale]. This figure illustrates the high quality of UTR-2 measurements and influence of turbulence in the propagation medium. The Sun radar experiments show, in some cases, the presence of high probability detected signals reflected from the Sun's corona [Figure 5, measurement by equipment described in Section 2.2; Figures 6-11, measurement by equipment described in Section 2.3]. The results of final processing for each day of observation in 1997 will be presented in future reports of Naval Research Laboratory. During this project, a theory of reflection from a high turbulence plasma in the solar corona was developed. This theory provides a good explanation of the results of the J. C. James solar radar experiments at 38 MHz, and was applied to our investigations at 8.9 MHz.

4. Conclusion

Special facilities and detection procedures were developed and placed in regular operation on the UTR-2 radiotelescope for sun and moon radar experiments. These facilities allowed us to reduce interference effects and to reach the maximum of sensitivity. Methods of checking ionospheric conditions simultaneously with the sun and moon radar experiments were developed. The signal reflected from the moon was detected with high reliability. The sun experiment required additional steps of observations and processing, especially when solar activity becomes higher. It is planned to continue coordinate active and passive methods of solar radar investigations, such as comparison of results from ground-based solar patrols and satellite observations with the results of our analysis. Undoubtedly, the solar radar experiments must be continued to further develop our techniques. During his visit at the UTR-2 observatory on 13 to 21 September 1997 and on 27 June to 7 July 1998, Dr. Rodriguez was familiarized with the facility, methods, and results of the experiments.

A. A. Konovalenko
Head of Decameter Radio Astronomy Department
Institute of Radio Astronomy
Kharkov, Ukraine

Національна Академія Наук України
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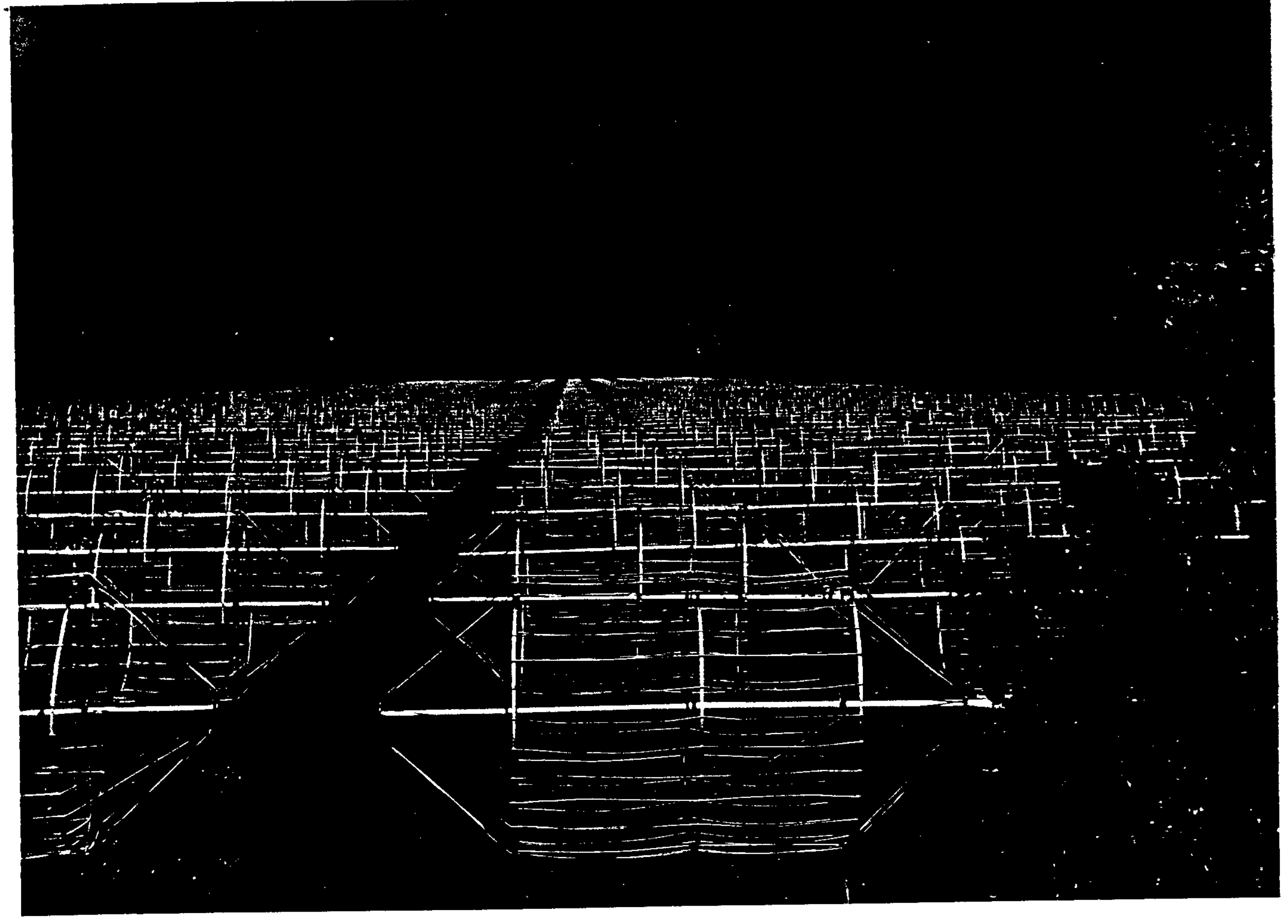


Fig. 1.

Fig. 2.

One example of data recorded for Moon observations

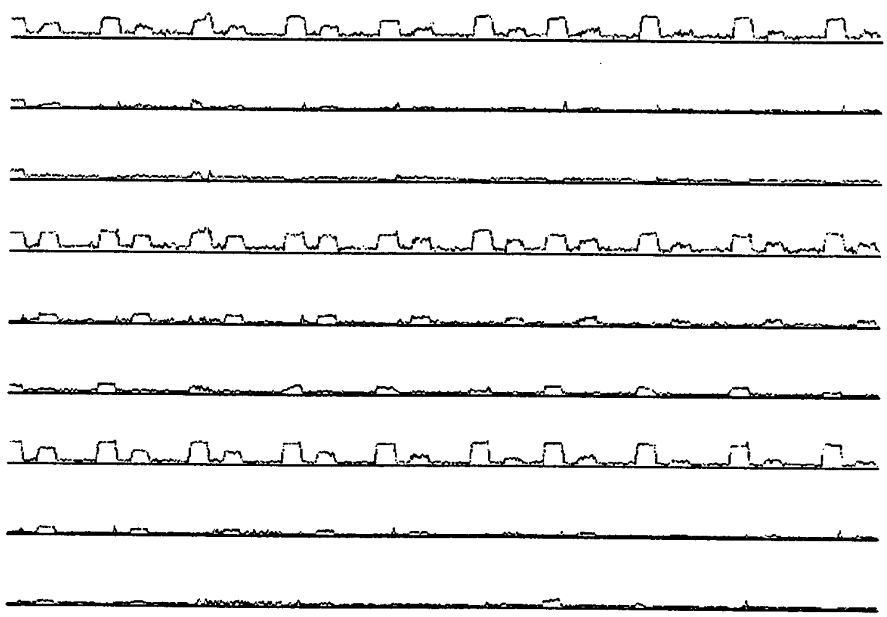


Figure 3

ll array;
beam mode;
dulation mode;
= 1 min.

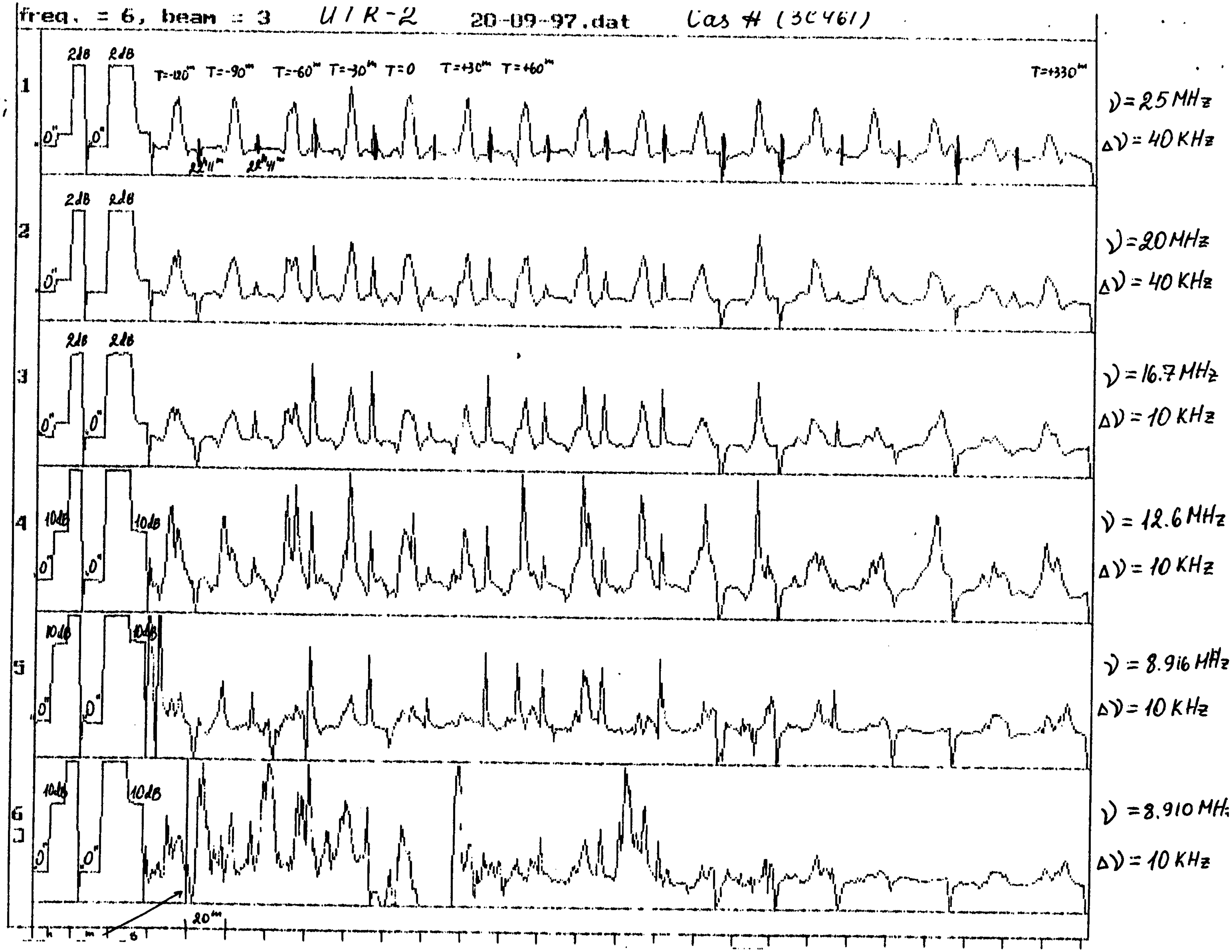


Fig. 4

The high probability detected signals reflected from the Sun's corona

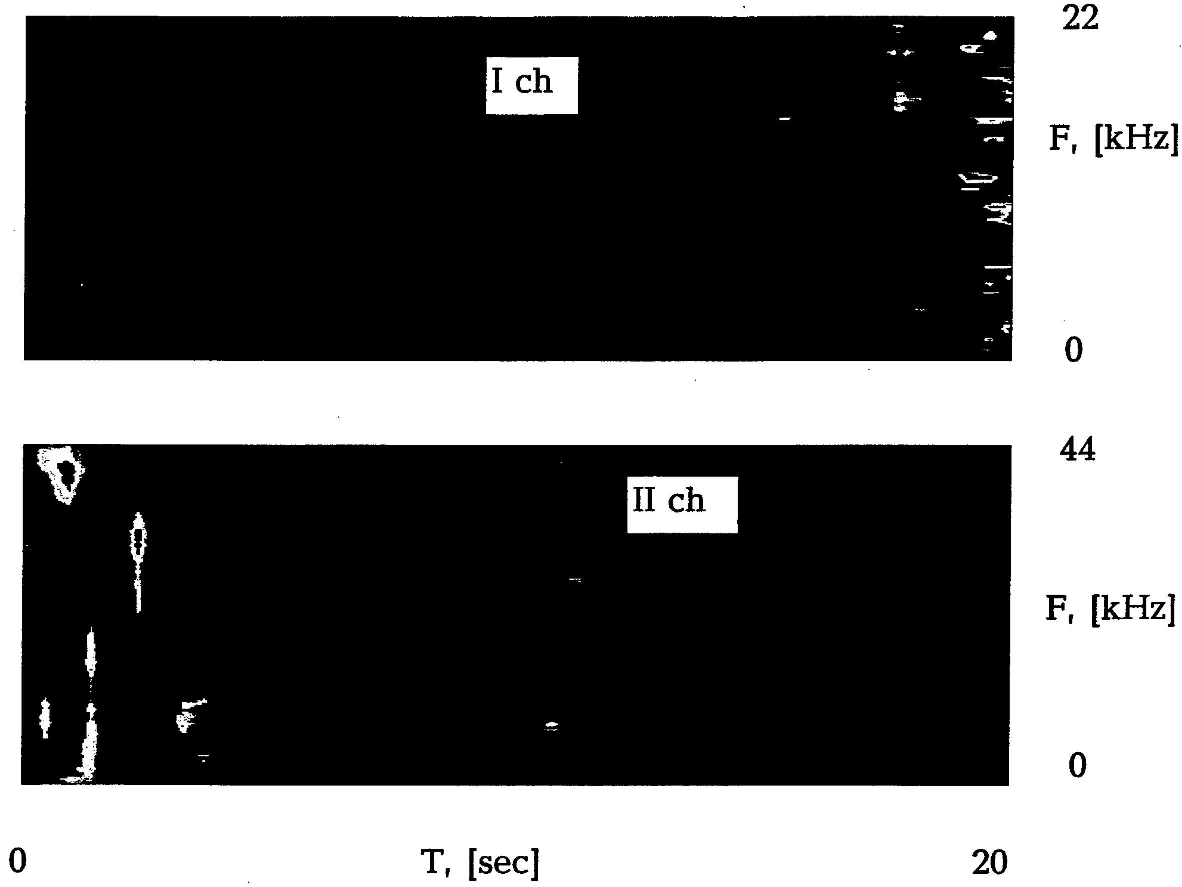
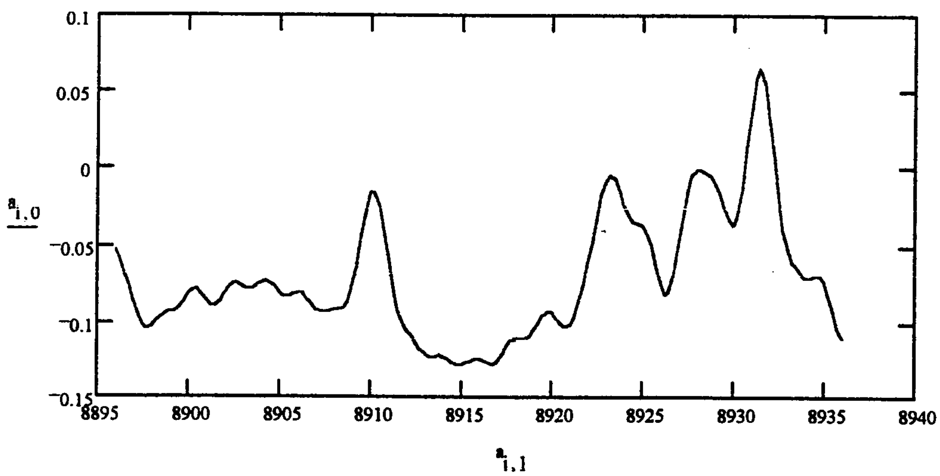


Figure 5.

I ch - Dynamic spectra at A channel,
II ch - Dynamic spectra at B channel,
The time and frequency coordinates have arbitrary start points.
Dynamic range 0.5 dB.

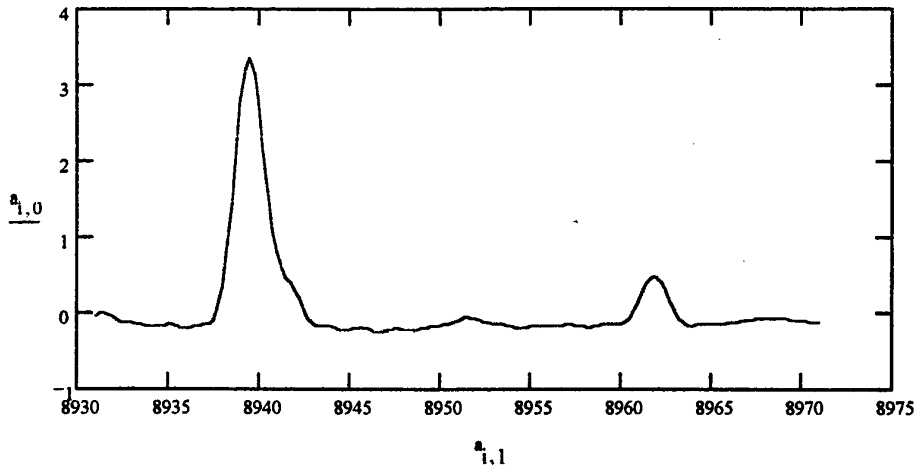


$a_{i,0}$ - relative intensity of the spectral features;

$a_{i,1}$ - frequency, kHz

Fig. 6

Average spectrum measured in the direction of the Sun during supposed reflected signal. Date : 8-23-1997.

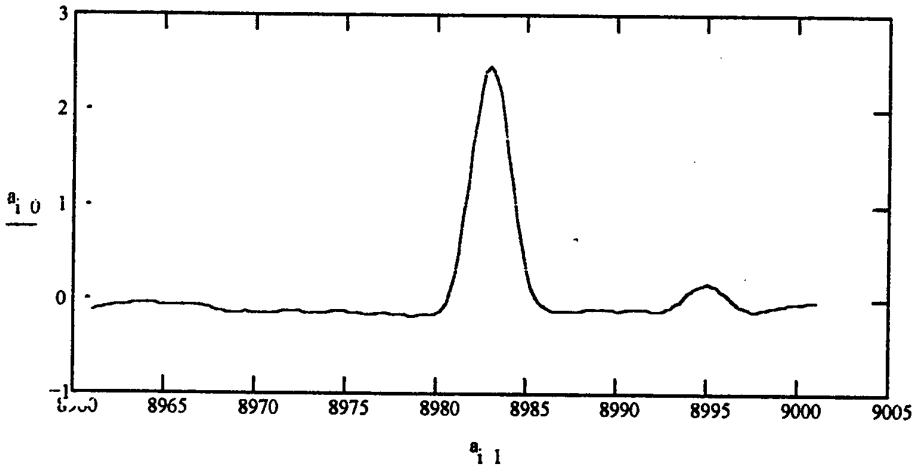


$a_{i,0}$ - relative intensity of the spectral features;

$a_{i,1}$ - frequency, kHz

Fig. 7

Average spectrum measured in the direction of the Sun during supposed reflected signal. Date : 8-23-1997.

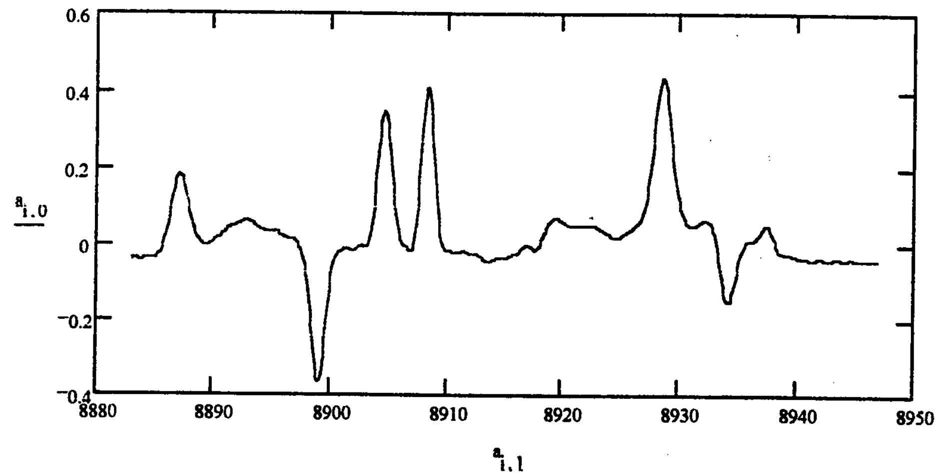


$a_{i,0}$ - relative intensity of the spectral features;

$a_{i,1}$ - frequency, kHz

Fig. 8

Average spectrum measured in the direction of the Sun during supposed reflected signal. Date : 8-23-1997.

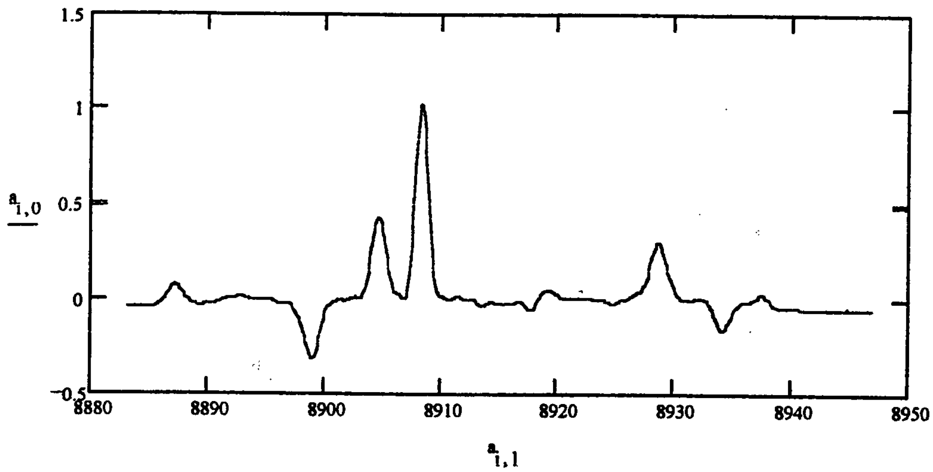


$a_{i,0}$ - relative intensity of the spectral features;

$a_{i,1}$ - frequency, kHz

Fig. 9

Average spectrum measured in the direction of the Sun during supposed reflected signal. Date : 7-4-1998.

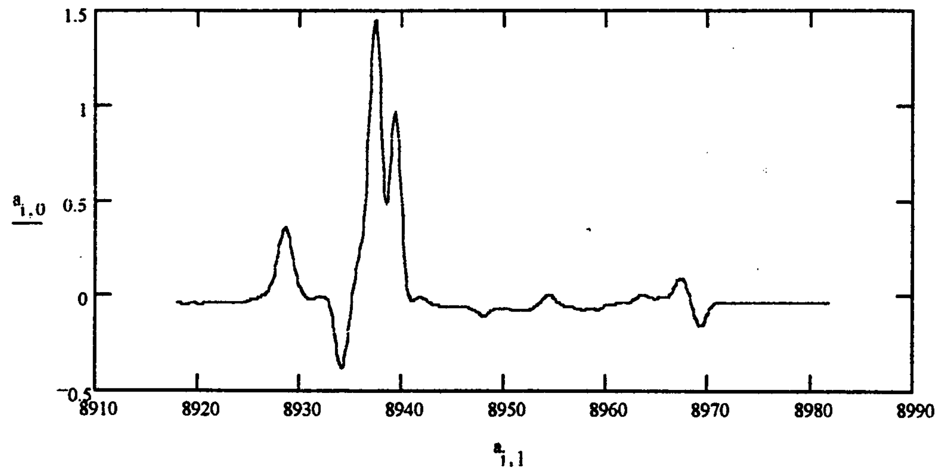


$a_{i,0}$ - relative intensity of the spectral features;

$a_{i,1}$ - frequency, kHz

Fig. *10*

Average spectrum measured in the direction shifted from the direction of the Sun on 1.5° during supposed reflected signal. Date : 7-4-1998.



$a_{i,0}$ - relative intensity of the spectral features;

$a_{i,1}$ - frequency, kHz

Fig. 11

Average spectrum measured in the direction of the Sun during supposed reflected signal. Date : 7-4-1998.